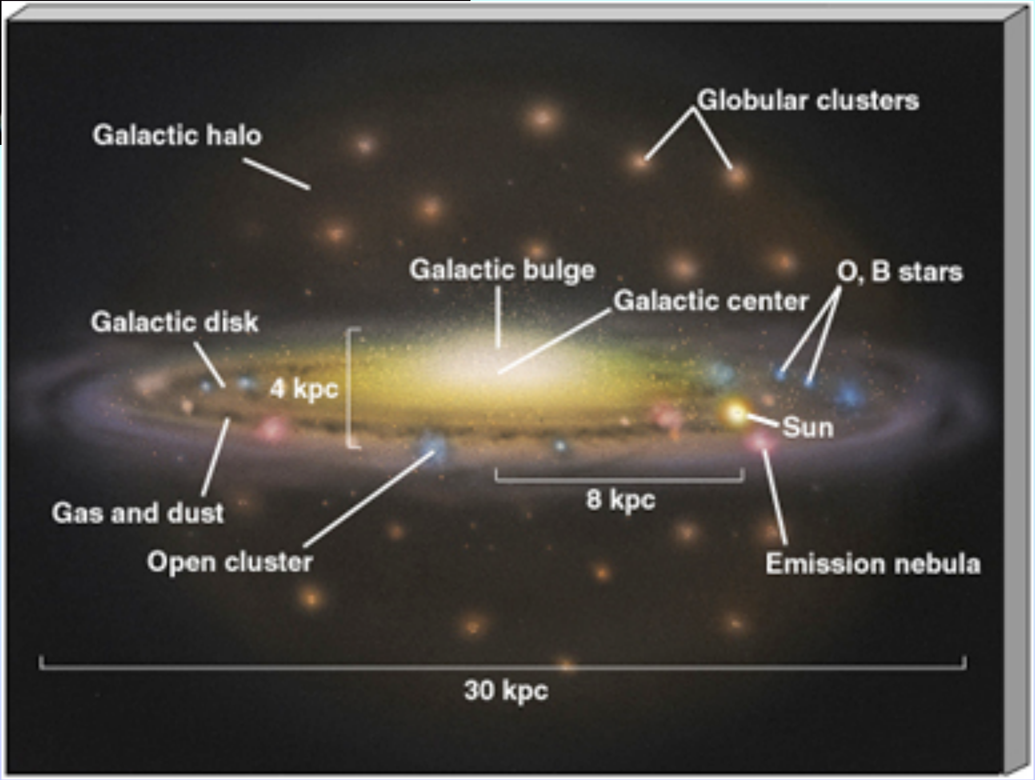
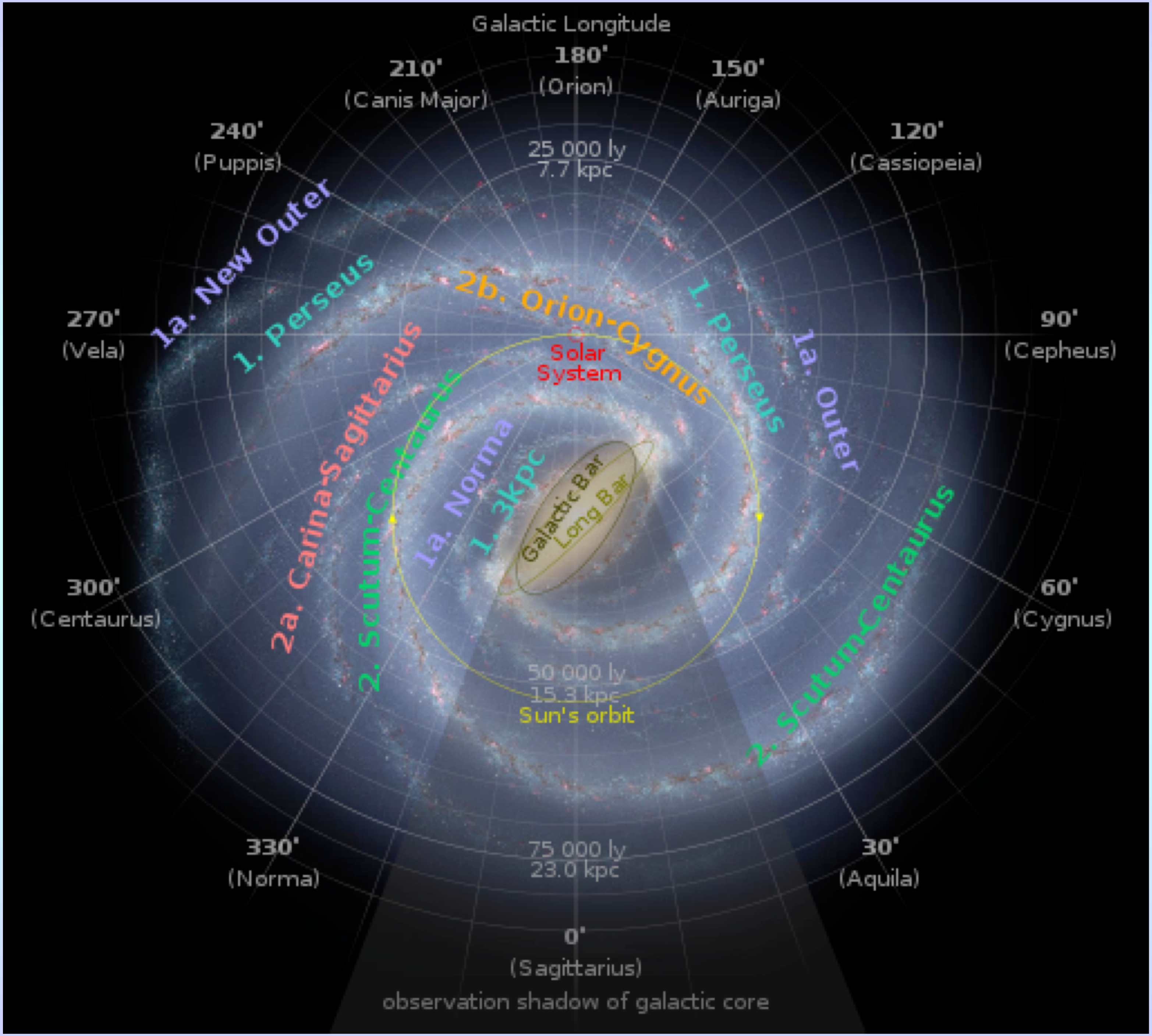
Far-IR all-sky image of the Milky Way

Schematic of the Galaxy




Galactic Longitude
180°
(Orion)
210°
(Canis Major)
150°
(Auriga)
240°
(Puppis)
120°
(Cassiopeia)
25 000 ly
7.7 kpc
1a. New Outer
1. Perseus
2b. Orion-Cygnus
1. Perseus
1a. Outer
270°
(Vela)
90°
(Cepheus)
Solar
System
2a. Carina-Sagittarius
2. Scutum-Centaurus
1a. Norma
1. 3kpc
Galactic Bar
Long Bar
2. Scutum-Centaurus
300°
(Centaurus)
60°
(Cygnus)
50 000 ly
15.3 kpc
Sun's orbit
330°
(Norma)
75 000 ly
23.0 kpc
30°
(Aquila)
0°
(Sagittarius)
observation shadow of galactic core

Parameterization

The Milky Way (and other spiral galaxies) are usually described via several components:

- Thin Disk: the area where most of the cold ISM and young stars reside. The scale height of this area is ~ 300 pc. The Sun is about ~ 25 pc above the Galactic plane.
- Thick Disk: a "puffed up" disk with scale height ~ 1 kpc. In the solar neighborhood, this component is ~10% that of the thin disk.
- Bar: an intermediate age (~ 3 Gyr) bar, oriented close to the line of sight.
- Halo: A slightly flattened ($b/a \sim 0.6$) distribution of old stars extending ~ 40 kpc. In the solar neighborhood, the halo density is ~ 0.5 % of the thin disk.
- Dark Halo: A dark (roughly spherical?) halo extending from ~ 50 to ~ 100 kpc.

The Rotation Curve

Most H I is rotating about the center of the Galaxy. At any Galactic longitude, l, we should see gas with radial velocities

$$V_r = r\omega\cos\theta - R_\odot \omega_\odot \sin l$$

From the law of sines

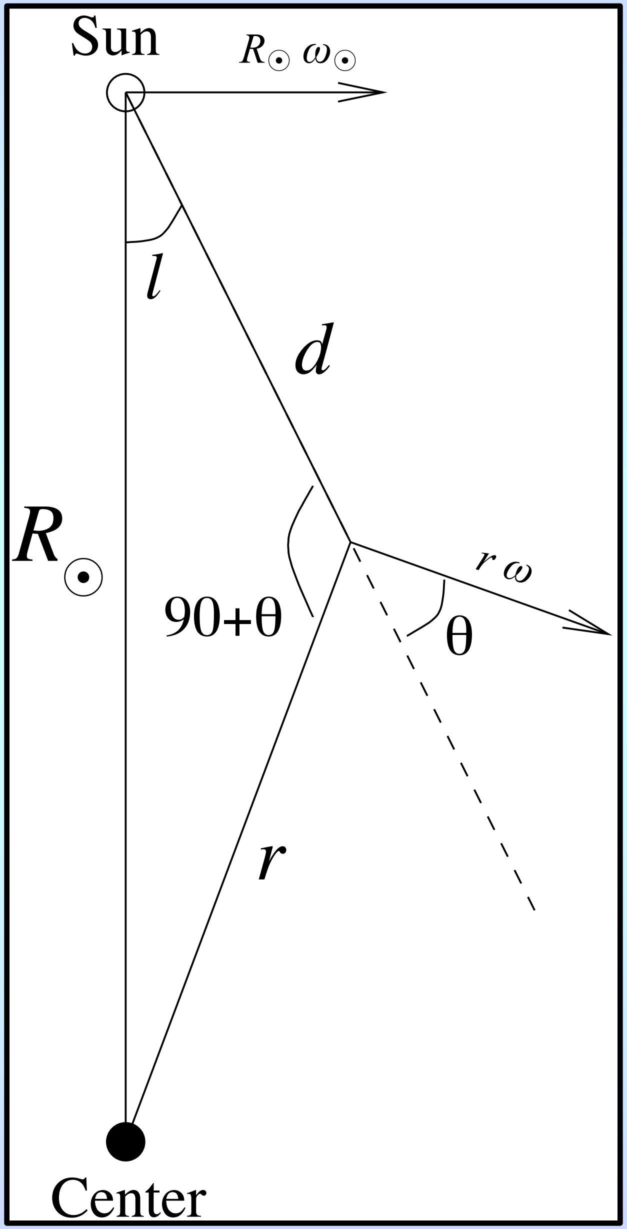
$$\frac{\sin l}{r} = \frac{\sin(90+\theta)}{R_\odot} = \frac{\cos\theta}{R_\odot}$$

So

$$V_r = R_\odot \omega \sin l - R_\odot \omega_\odot \sin l = R_\odot(\omega - \omega_\odot)\sin l$$

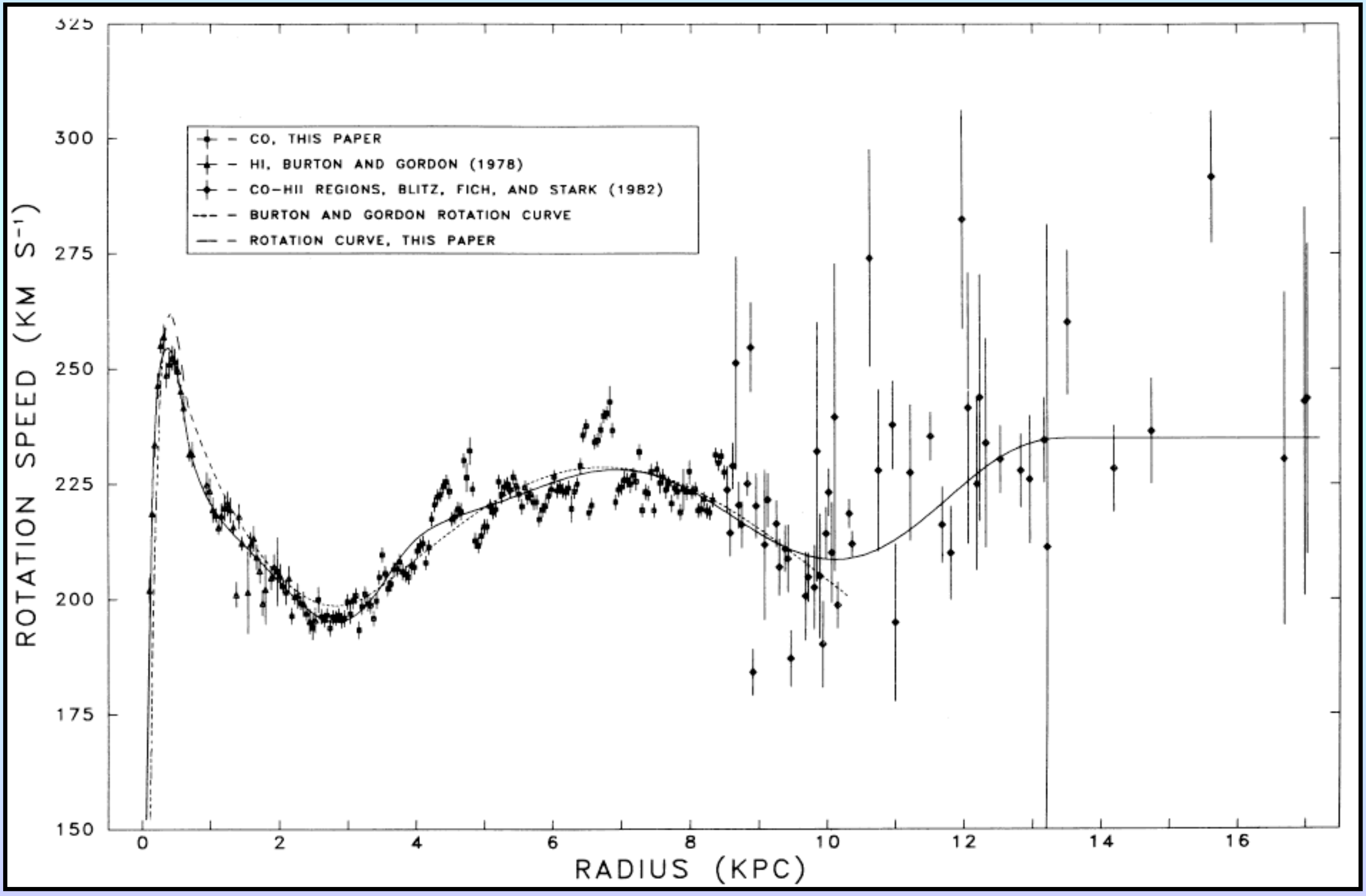
Since the maximum velocity is obtained when the gas motion is along the line-of-sight, i.e., at $r_T = R_\odot \sin l$, we can use this to derive the Milky Way's rotation curve, $\omega(r_T)$

$$V_{\max} = R_\odot\left[\omega(r_T) - \omega_\odot\right]\sin l$$



Milky Way Rotation Curve

At $R < 3$ kpc, the derived curve is strongly affected by the breakdown of the circular motion hypothesis due to the central bar.



The Local Shear and Vorticity: Oort Constants

The traditional method for describing the *local* behavior of the Galactic disk is through Oort Constants. We begin with the observed radial velocity

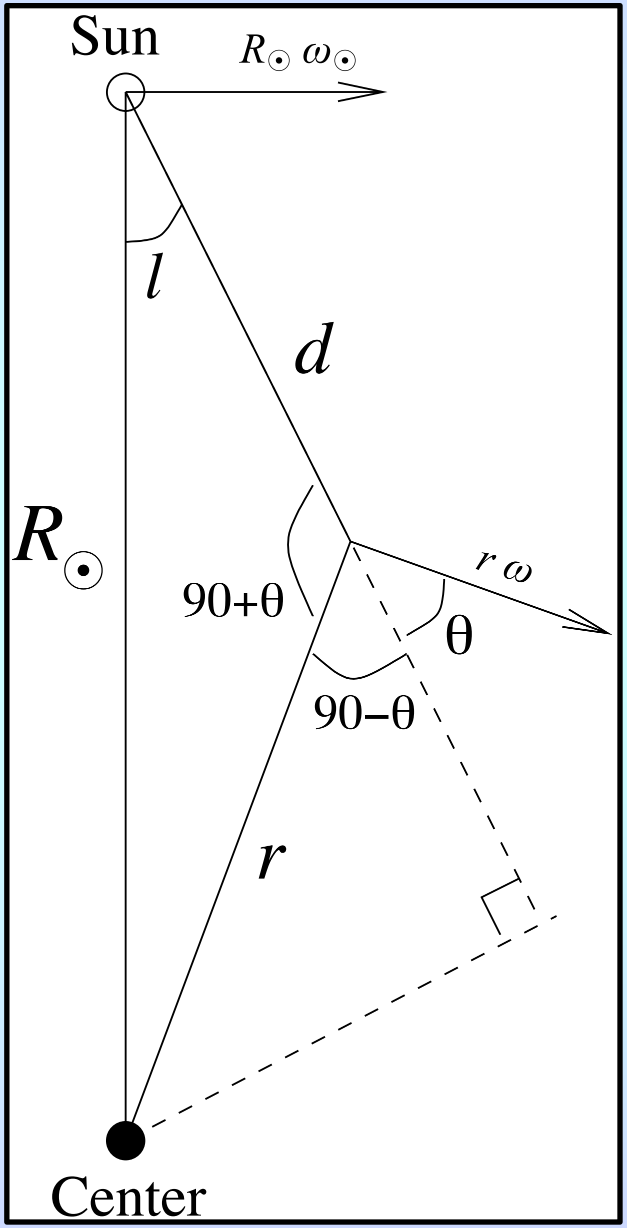
$$V_R = R_\odot(\omega - \omega_\odot)\sin l$$

If $\Theta(r) = r\,\omega$ is the circular velocity at r, then to first order

$$\omega - \omega_\odot = \left(\frac{d\omega}{dr}\right)_{R_\odot}(r - R_\odot)$$

$$= \left\{\frac{1}{R_\odot}\left(\frac{d\Theta}{dr}\right)_{R_\odot} - \frac{\Theta_\odot}{R_\odot^2}\right\}(r - R_\odot)$$

But for small distances, $R_\odot - r \sim d\cos l$, so



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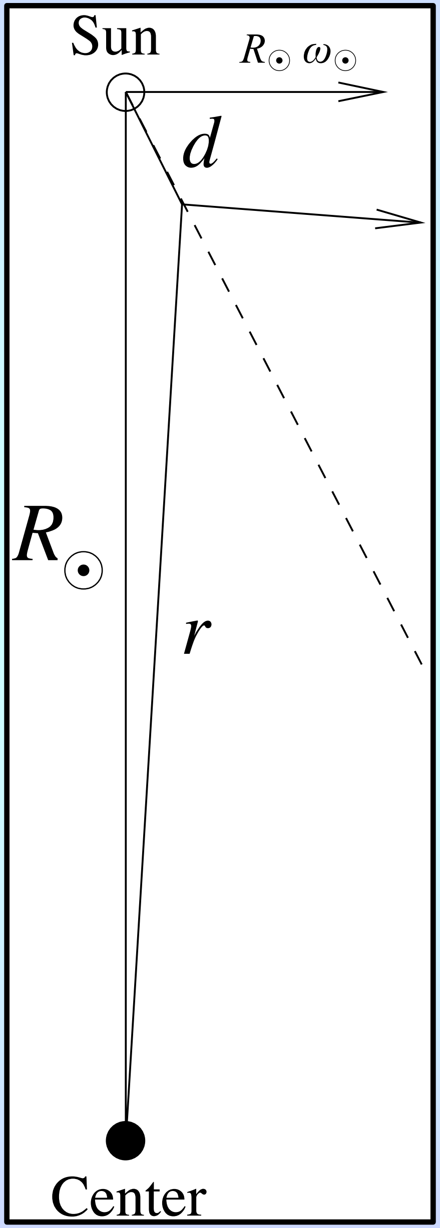


The Local Shear and Vorticity: Oort Constants

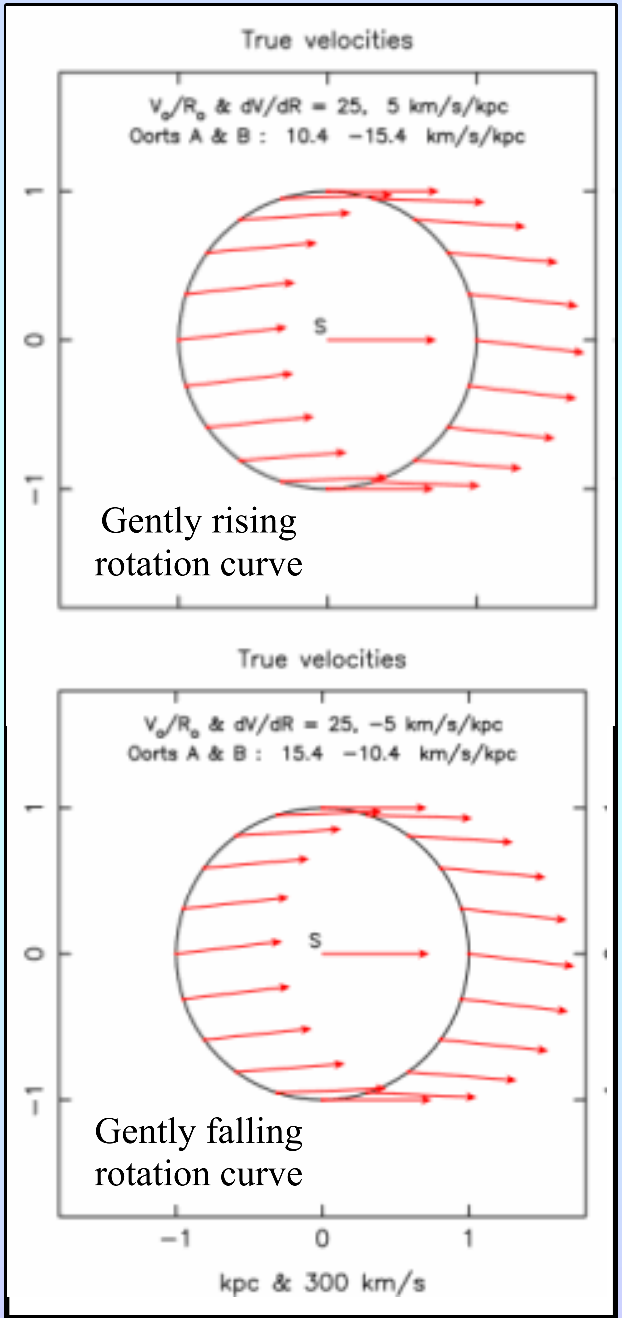
$$V_R = R_\odot \left\{ \frac{1}{R_\odot} \left(\frac{d\Theta}{dr} \right)_{R_\odot} - \frac{\Theta_\odot}{R_\odot^2} \right\} (r - R_\odot) \sin l$$

$$\approx \left\{ \frac{\Theta_\odot}{R_\odot} - \left(\frac{d\Theta}{dr} \right)_{R_\odot} \right\} d \sin l \cos l$$

$$\approx \frac{1}{2} \left\{ \frac{\Theta_\odot}{R_\odot} - \left(\frac{d\Theta}{dr} \right)_{R_\odot} \right\} d \sin 2l$$

$$\approx A\ d\ \sin 2l$$

The Oort Constant $A \sim 13$ km/s/kpc describes the shear in the local velocity field.



The Local Shear and Vorticity: Oort Constants

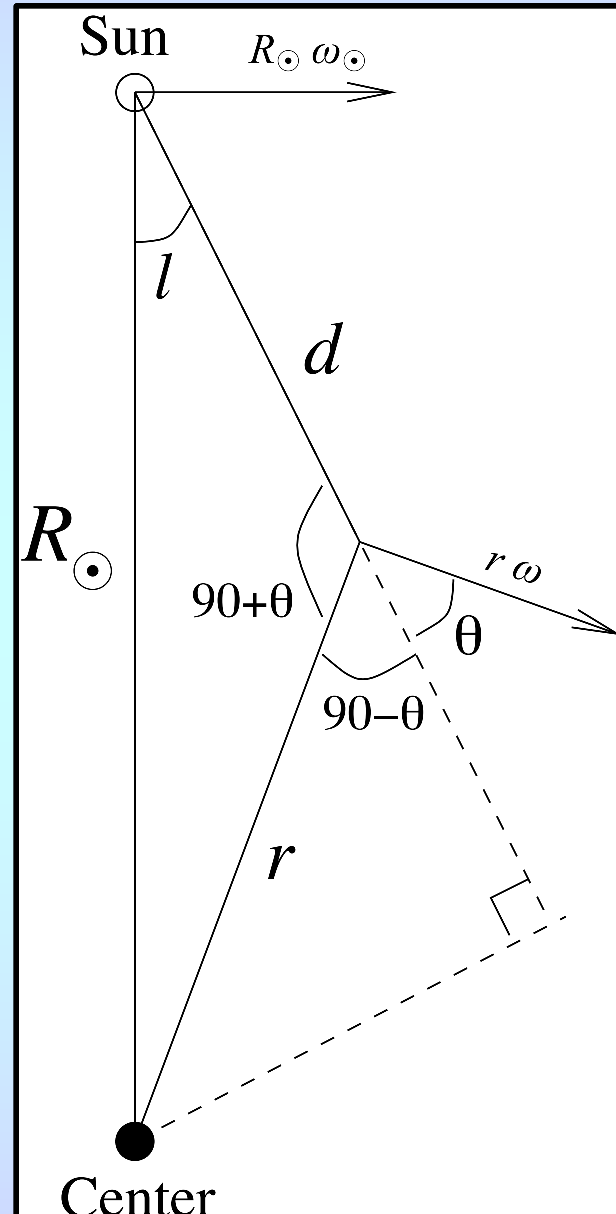
Alternatively, if we consider the transverse (i.e., the proper) motion of nearby objects

$$
\begin{aligned}
V_T &= r\omega \sin\theta - R_\odot \omega_\odot \cos l \\
&= \omega\left(R_\odot \cos l - d\right) - R_\odot \omega_\odot \cos l \\
&= R_\odot\left(\omega - \omega_\odot\right)\cos l - \omega\, d
\end{aligned}
$$

and expand $\omega\, d$ so that

$$
\begin{aligned}
\omega\, d &\approx d\left[\omega_\odot + \left(\frac{d\omega}{dr}\right)_{R_\odot}\left(r - R_\odot\right) + \ldots\right] \\
&\approx \omega_\odot d - \left(\frac{d\omega}{dr}\right)_{R_\odot} d^2 \cos l
\end{aligned}
$$

If we now substitute this in, along with our previous expression for $\omega - \omega_\odot$, then



The Local Shear and Vorticity: Oort Constants

$$V_T = \left[\left(\frac{d\Theta}{dr}\right)_{R_\odot} - \frac{\Theta_\odot}{R_\odot}\right](r - R_\odot)\cos l - \omega_\odot d$$

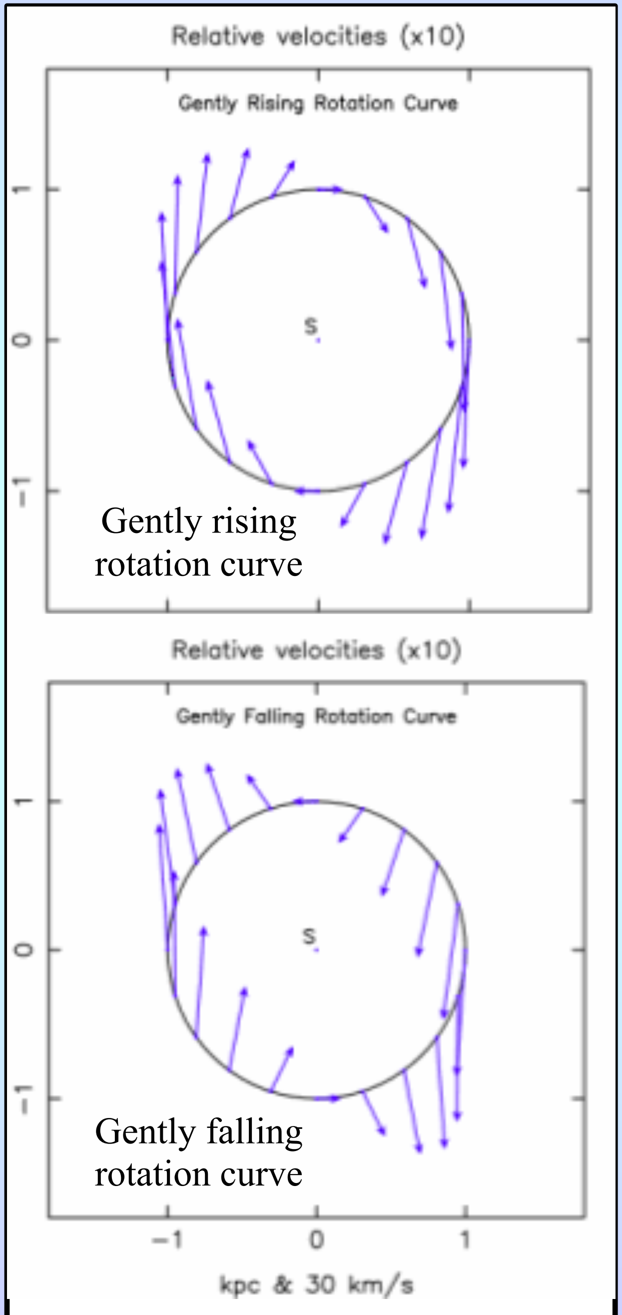
$$= \left[\frac{\Theta_\odot}{R_\odot} - \left(\frac{d\Theta}{dr}\right)_{R_\odot}\right] d\cos^2 l - \frac{\Theta_\odot}{R_\odot} d$$

Finally, if we use $\cos^2 l = ½(1+\cos 2l)$, and note that the proper motion, $\mu = V_T / 4.74\, d$,

$$V_T = \frac{1}{2}\left[\frac{\Theta_\odot}{R_\odot} - \left(\frac{d\Theta}{dr}\right)_{R_\odot}\right] d\cos 2l - \frac{1}{2}\left[\frac{\Theta_\odot}{R_\odot} + \left(\frac{d\Theta_\odot}{dr}\right)_{R_\odot}\right] d$$

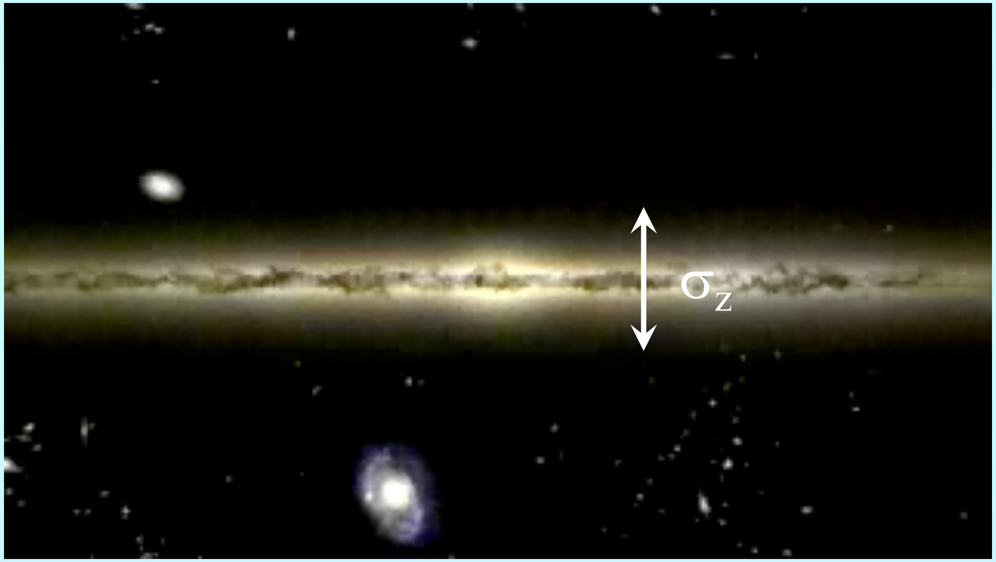
$$= d(A\cos 2l + B) \quad \text{and} \quad \mu = \frac{A\cos 2l + B}{4.74}$$

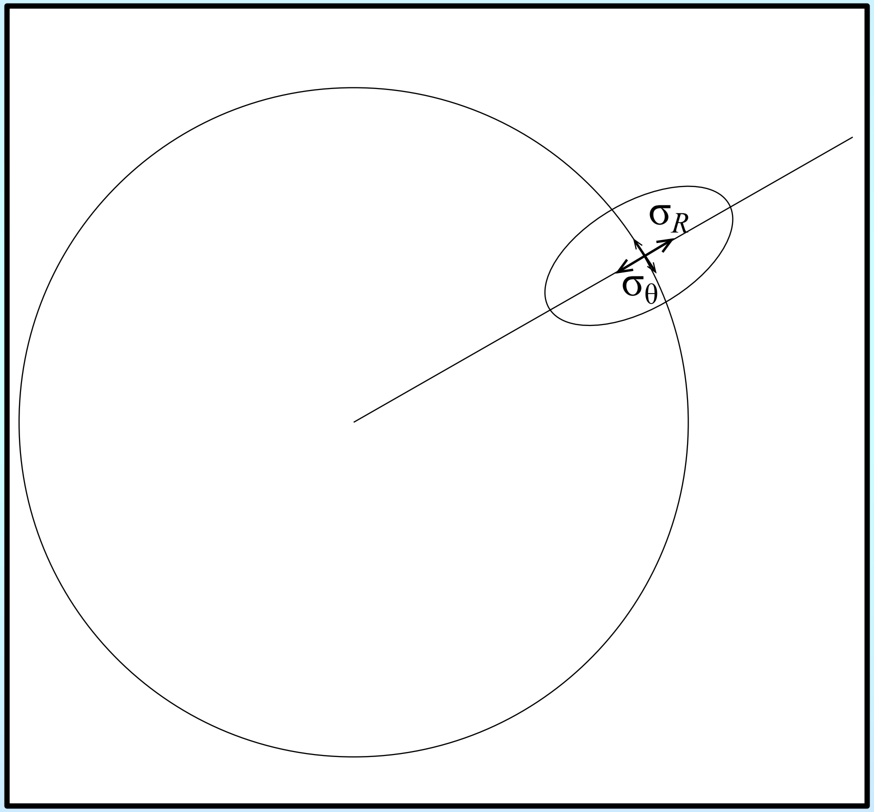
The coefficient $B = -10.2$ km/s/kpc describes the local rotation of the solar neighborhood; it can be measured from proper motion data without any knowledge of distance.



Velocity Ellipsoid

The stars in the solar neighborhood are not orbiting together. While V_{rot} describes their bulk motion, their residuals are described by a velocity ellipsoid, σ_R, σ_θ, and σ_z.





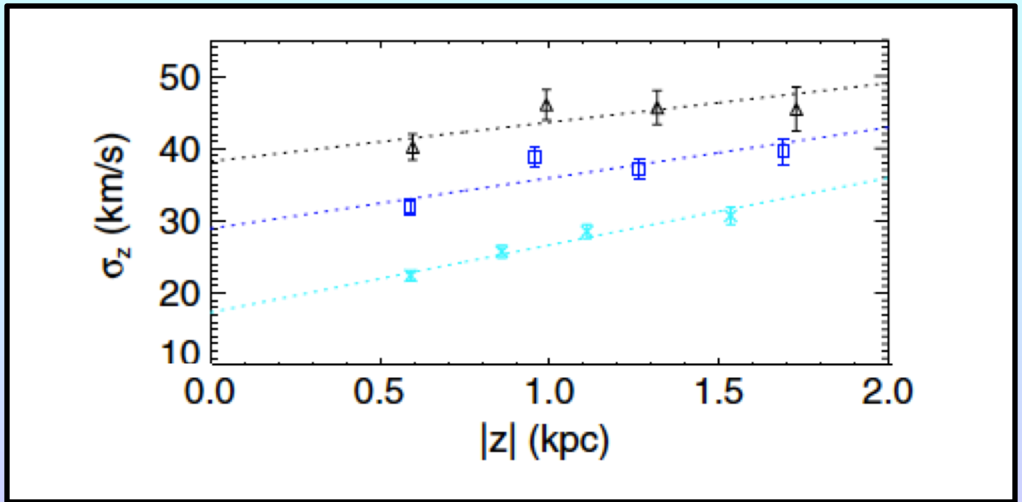
The values σ_R and σ_θ probe the disk scattering and place constraints on stability. The vertical velocity dispersion, σ_z is more useful, as it allows us to measure disk mass.

Disk Thickness

The thickness of a disk galaxy is usually parameterized via an exponential, $N(z) \propto \exp\{-z / z_0\}$.

Object	Age	Scale Height	σ_z
O stars	$\sim 3 \times 10^6$	~ 50 pc	~ 5 km/s
B stars	$\sim 1.5 \times 10^7$	~ 60 pc	~8 km/s
A stars	$\sim 5 \times 10^8$	~ 120 pc	~ 9 km/s
F stars	$\sim 3 \times 10^9$	~ 190 pc	~ 11 km/s
G stars	$\sim 10 \times 10^9$	~ 340 pc	~ 15 km/s
K stars	$\sim 15 \times 10^9$	~ 350 pc	~ 17 km/s

The *z*-velocity dispersion is almost independent of height above the plane.



One Slide on Stellar Dynamics

The stellar distribution in the z-direction is related to σ_z through the Boltzmann and Poisson's equation. Stars are essentially collisionless particles moving through a 6-dimensional phase space (x, y, z, v_x, v_y, v_z). If ω is an object's 6-D coordinate, and $f(\omega)$ the distribution of stars, then by analogy to Euler's equation for fluids

$$\frac{\partial f}{\partial t} + \nabla \bullet \left(f \dot{\omega} \right) = 0$$

The collisionless Boltzmann equation is rarely used. Instead, one typically integrates over various quantities to derive a series of Jean's equations, which can then be combined with Poisson's equation to yield constraints on the mass distribution.

σ_z and Disk Mass

For thin disks, the Jeans equation in cylindrical coordinates can be written as

$$\frac{\partial}{\partial z}\left\{\frac{1}{\nu}\frac{\partial}{\partial z}\left(\nu\sigma_z^2\right)\right\} = -4\pi G\rho$$

where ν is the stellar density and ρ the mass density. This equation can be solved to yield the ν as a function of z and $\sigma_z(z)$. Note that if σ_z is independent of z (an isothermal disk), this further simplifies to

$$\frac{\partial}{\partial z}\left\{\frac{1}{\nu(z)}\frac{\partial \nu(z)}{\partial z}\right\} = -\frac{4\pi m G \nu(z)}{\sigma_z^2}$$

where m is the stellar mass. The solution to this equation is

$$\rho(z) = \rho_0 \operatorname{sech}^2\left(\frac{z}{2z_0}\right) \quad \text{where} \quad z_0 = \left(\frac{\sigma_z^2}{8\pi G\rho_0}\right)^{1/2}$$

Note that this leads to a simple relation between velocity dispersion and Σ, the surface mass of the disk:

$$\sigma_z^2 = 2\pi G \Sigma z_0$$

σ_z and Disk Mass

Note: a sech^2 law is not that different from an exponential disk.

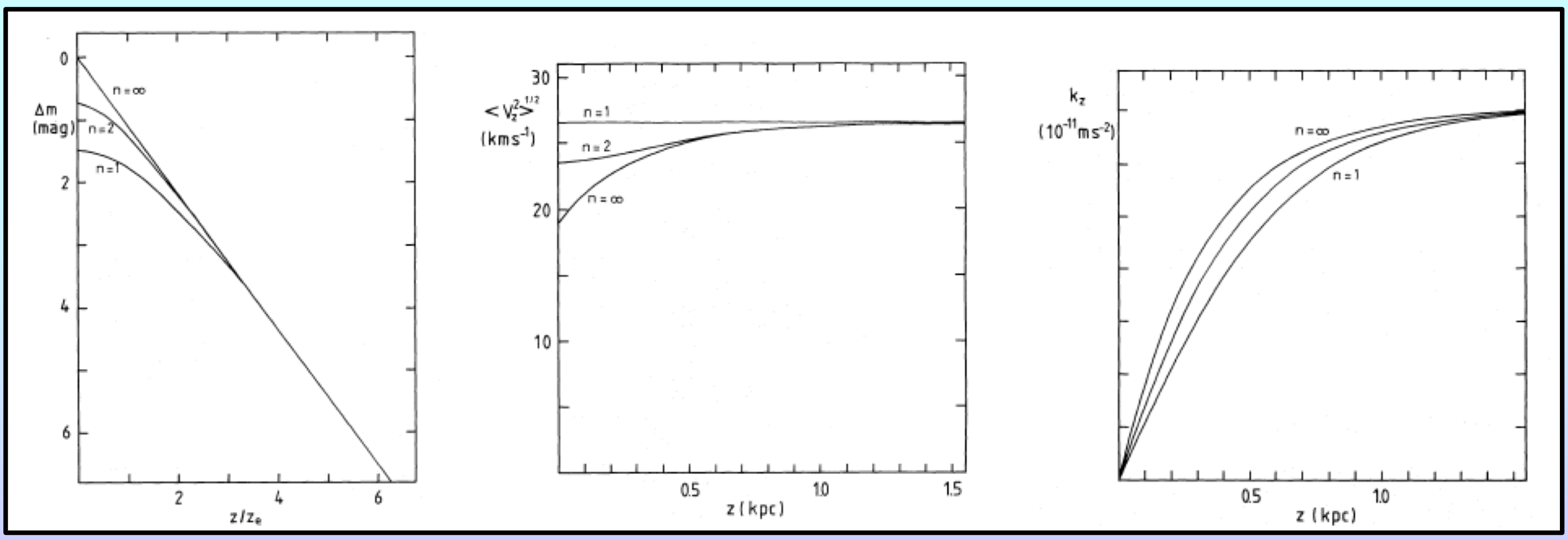
$$\operatorname{sech}(z) = \frac{1}{\cosh(z)} = \frac{2}{e^{z} + e^{-z}} \approx e^{-z}$$

In fact, there is a family of solutions for spiral disks. In general,

$$N(z) \propto \operatorname{sech}^{2/n}\left(\frac{nz}{2z_0}\right) \quad \text{where}$$

$n = 1$ implies an isothermal disk

$n = \infty$ implies an exponential disk

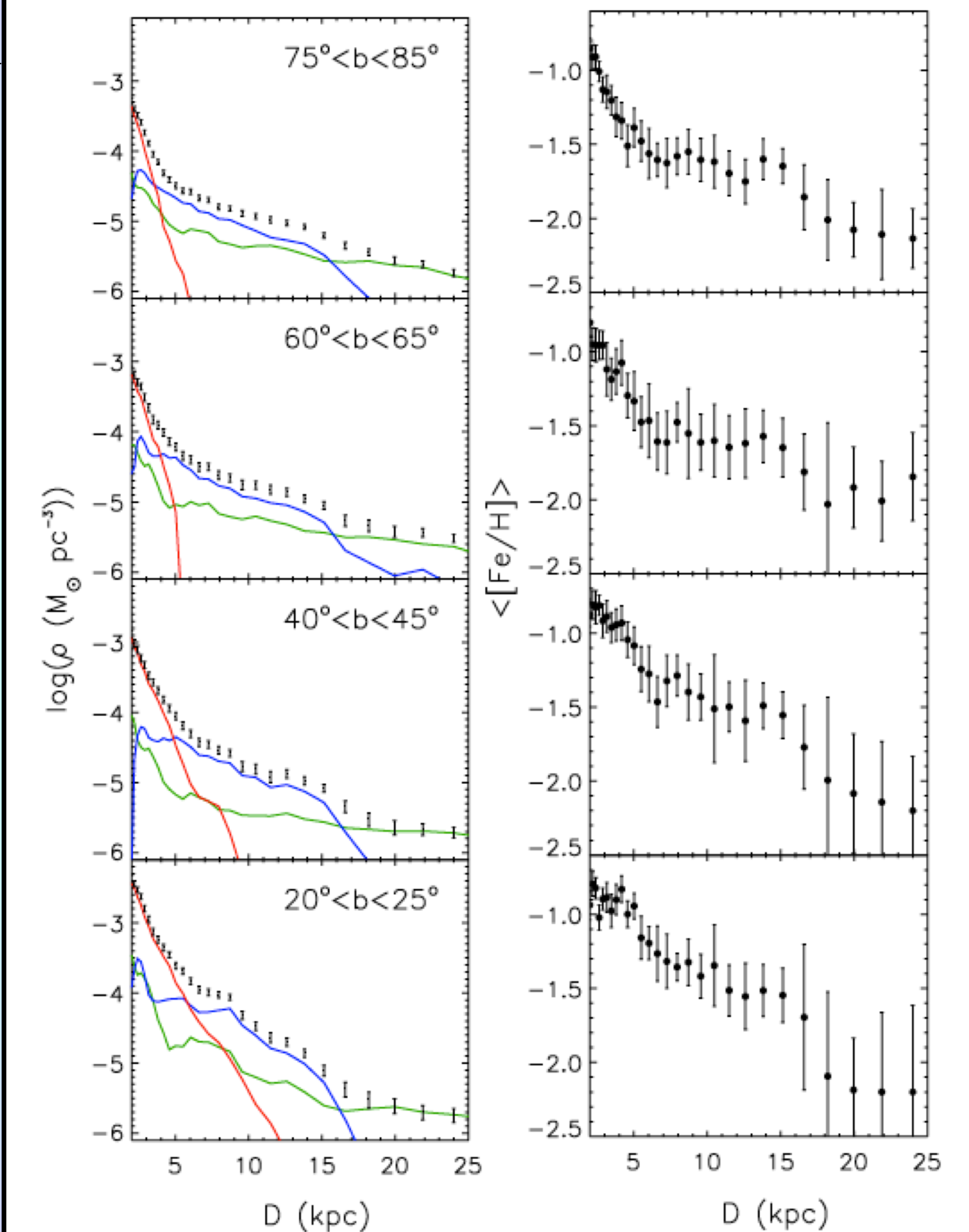


The Radial Distribution

Once outside the bar, the disk's surface brightness can best be fit with a simple exponential,

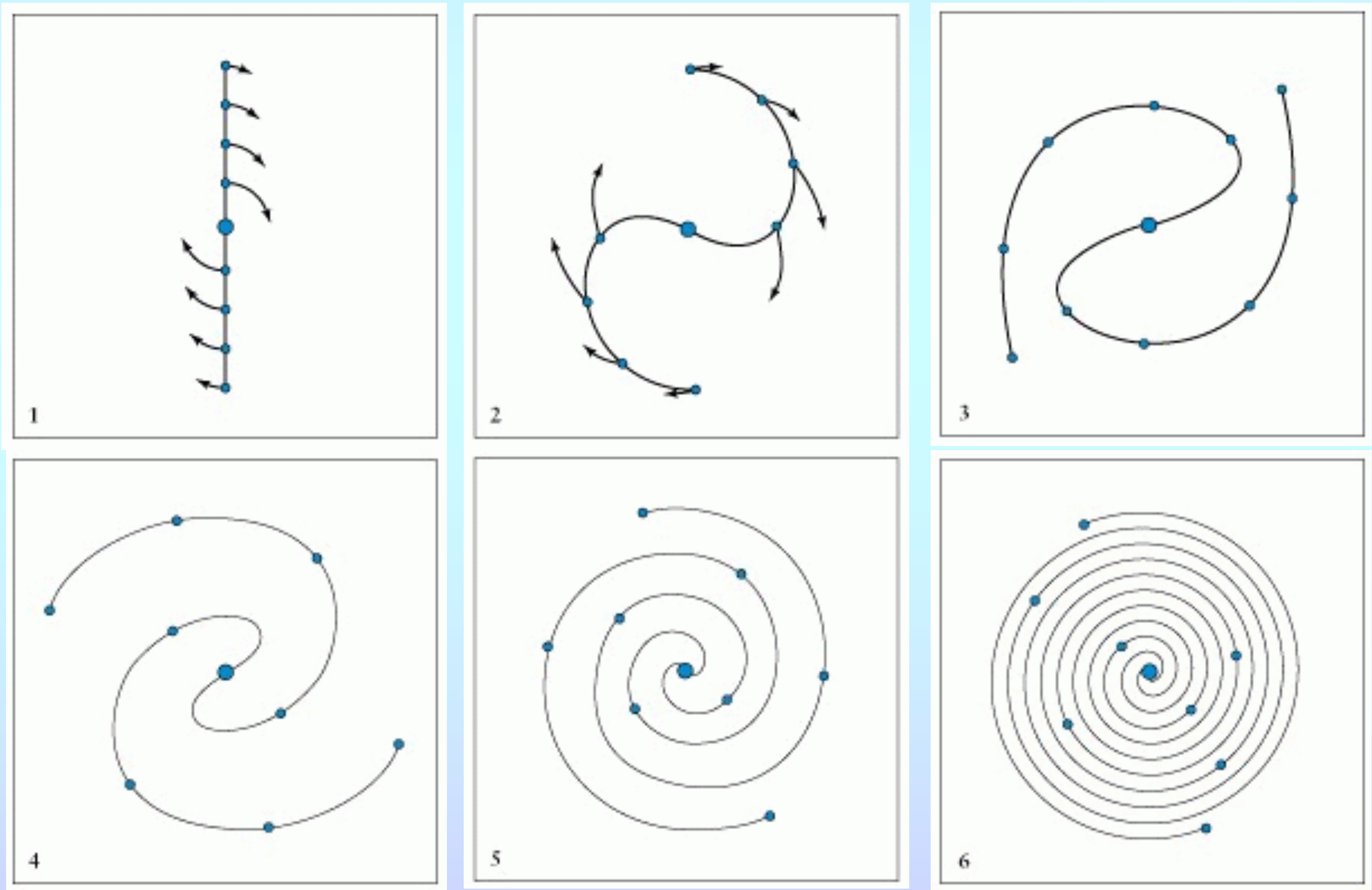
$$I(r) = I_0 \exp\left(-\frac{r}{r_0}\right)$$

The scale length, r_0, of the disk is somewhat controversial, but is likely ~ 3 kpc (for both the thin and thick components). The metallicity of the disk also declines with a somewhat similar scale length (though the α-elements may scale differently than the Fe-peak elements).

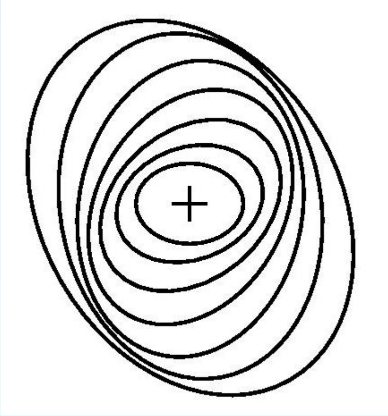


Spiral Arms

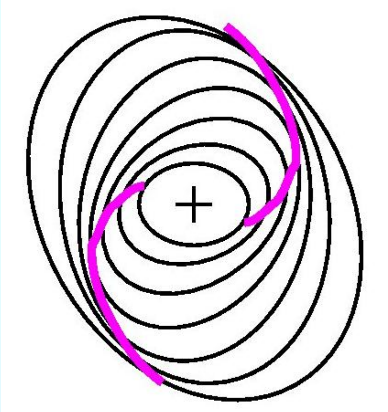
Because orbital frequency depends on distance, an initial line of stars will quickly be drawn out into a spiral, and wrapped up in just a few orbits. Arms like this can't last more than about ~ 1 Gyr.



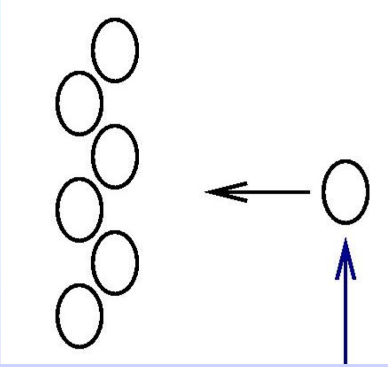
Spiral Density Waves



- The orbits in spiral galaxies are not quite circles – they are ellipses. These ellipses are slightly tilted with respect to each other.

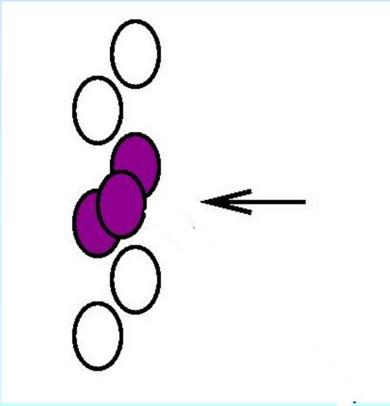


- Thus there are regions of slightly higher density than their surroundings. The higher density means higher gravity.

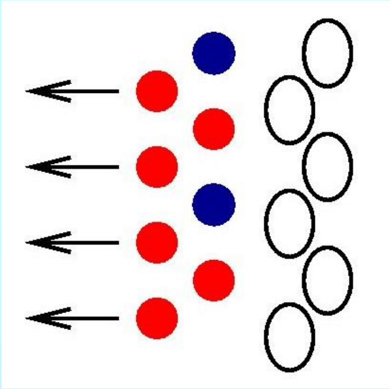


- An object (such as a gas cloud) will be attracted to these regions and will drift towards them.

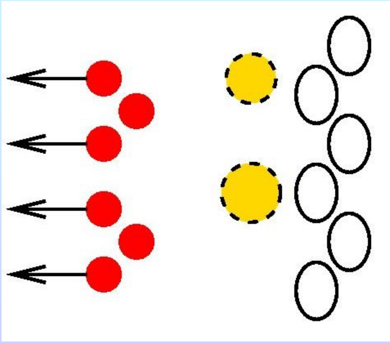
Spiral Density Waves



- When the gas cloud collides with other gas clouds, stars will be formed. (This is where most of the galaxy's star formation takes place.)



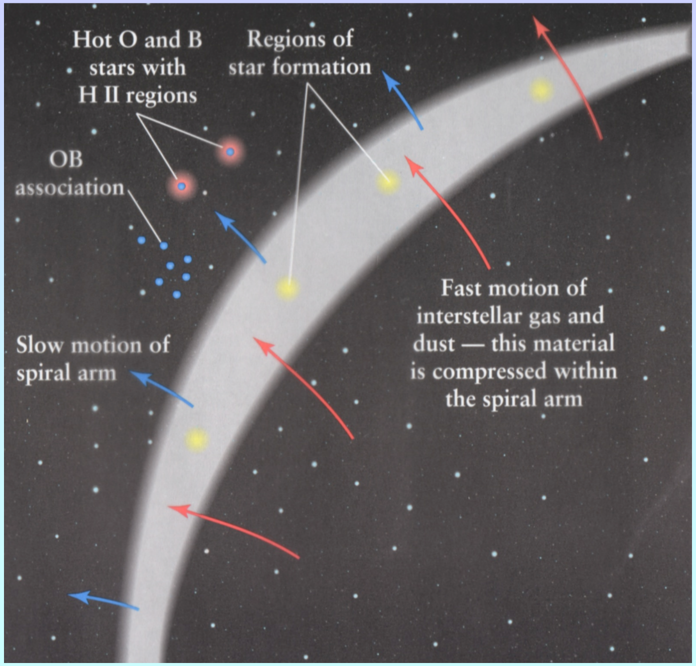
- Star will form over the whole range of stellar masses. A typical Initial Mass Function (IMF) is $N(M) \propto M^s$, with $s = -2.35$ (the Salpeter mass function). More modern IMFs do exist.

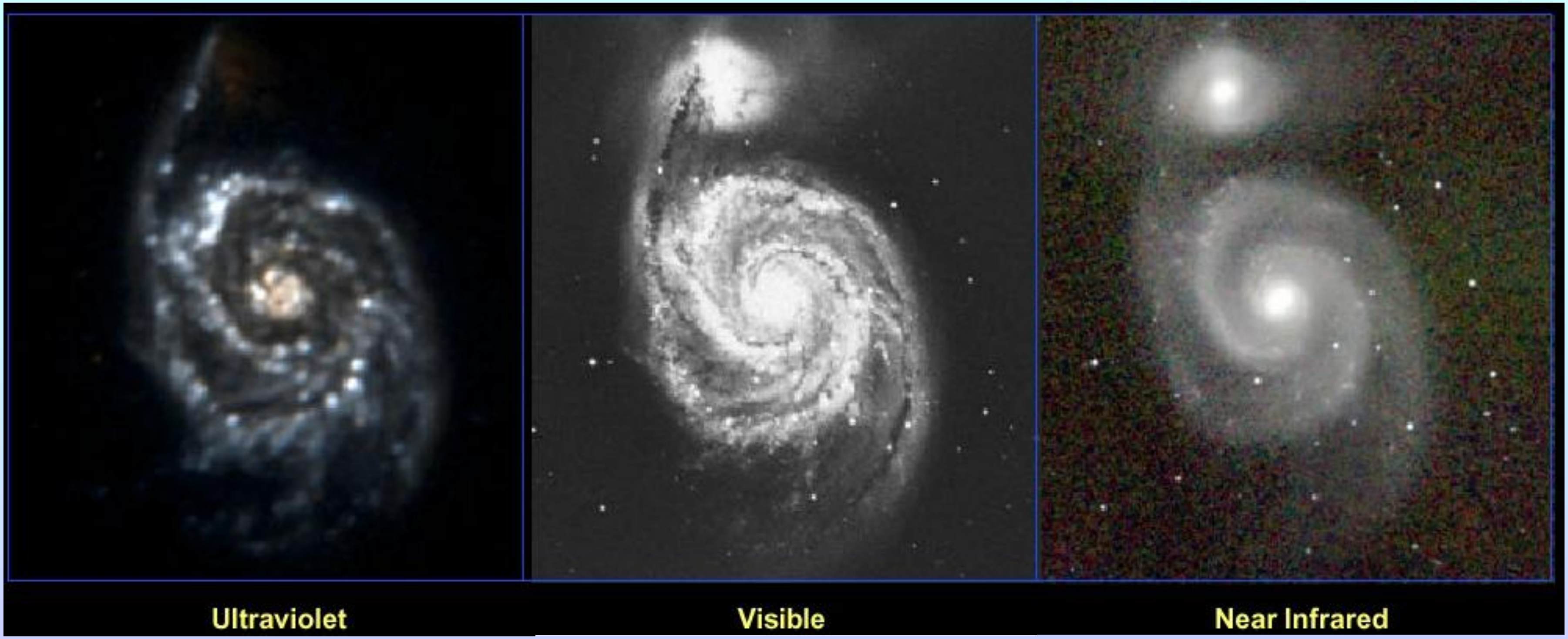


- High-mass (O and B main sequence) stars don't go far before they go supernova. The brightest (and bluest) of a galaxy's stars will never be far from the spiral arm.

Spiral Density Waves

Since all the bright blue stars die before leaving the spiral arm, the spiral density waves must show up better at ultraviolet wavelengths. In general, the density enhancement in the spiral arms is just a few percent.



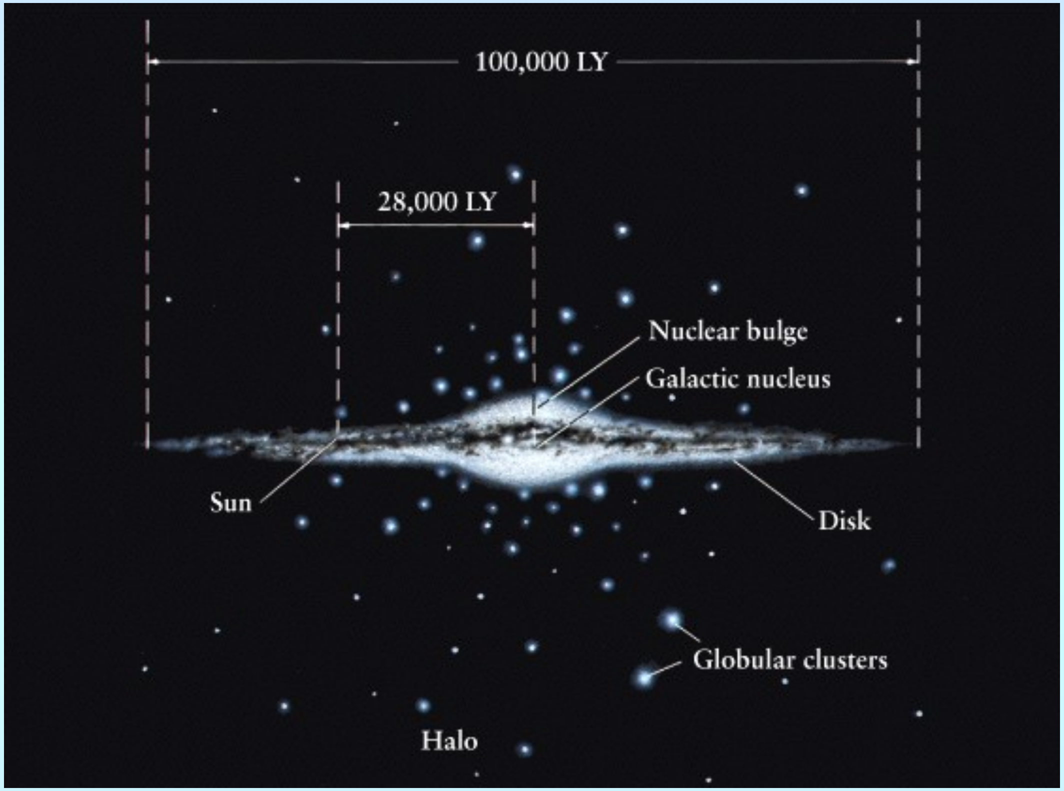


The Stellar Halo

The spheroidal component of the galaxy declines roughly as $\rho \propto r^{-n}$, with $n \sim 2.77$. Traditionally, this halo was thought to formed early on, before the collapse of the disk (Eggen, Lynden-Bell, & Sandage 1962). However, it is more likely that this component has been built up hierarchically through collisions with small galaxies. This component extends at least ~ 50 kpc.

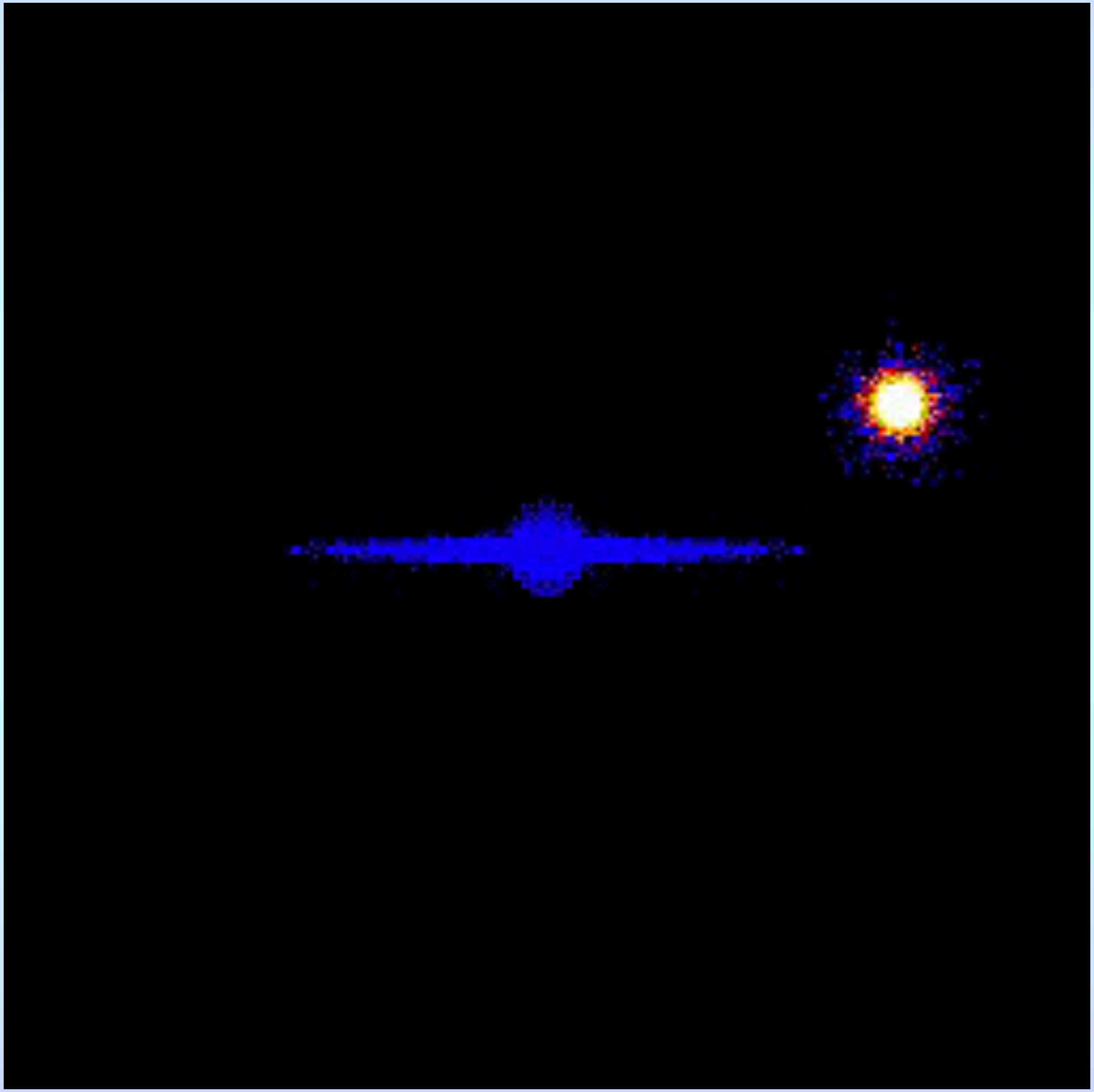
Halo stars are generally metal poor, and do not rotate with the disk. They are sometimes referred to as "high velocity stars", since their motions deviate substantially from the local standard of rest.

Milky Way Cannibalism

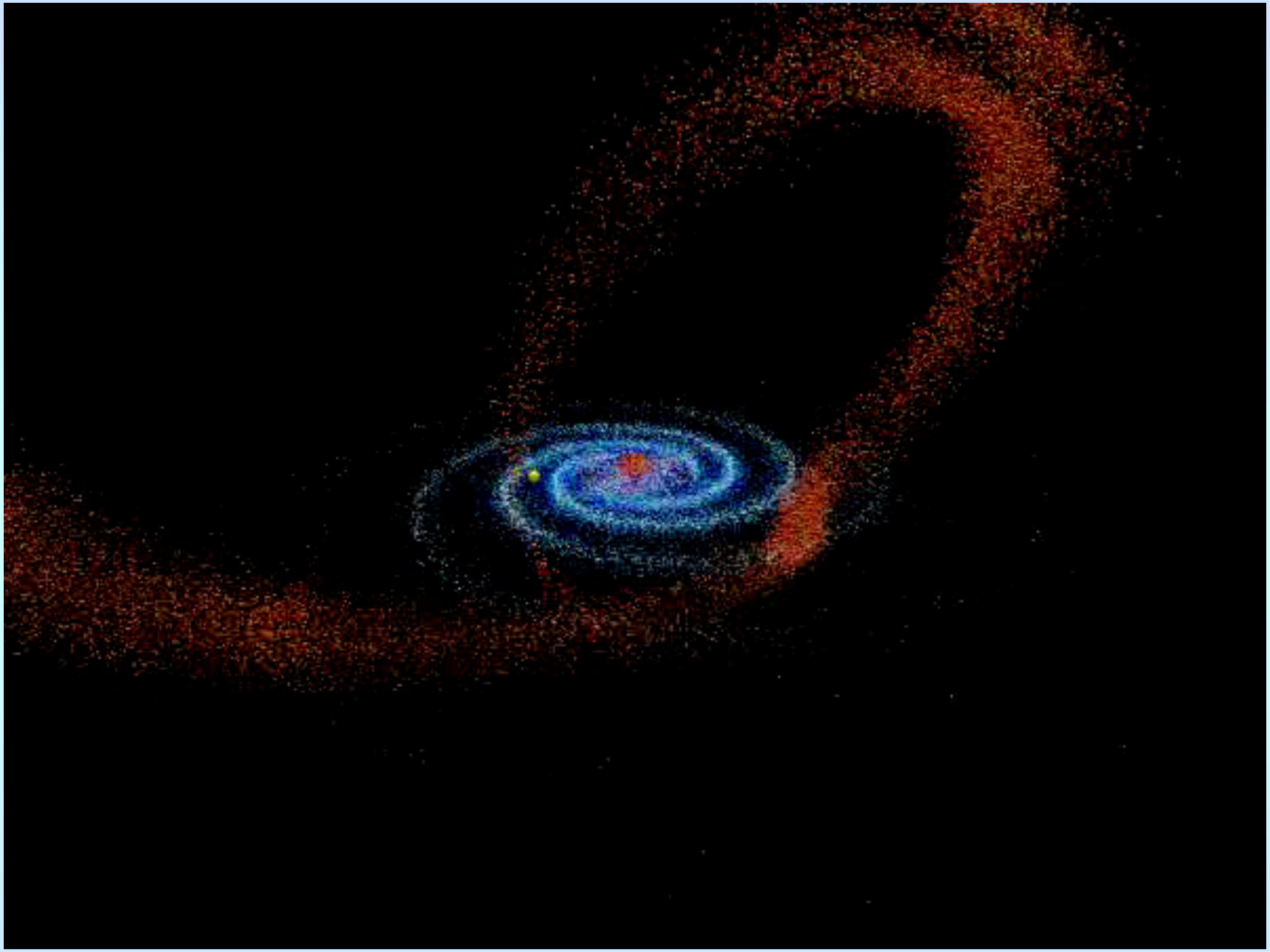


 ←A small dwarf galaxy

Milky Way Cannibalism

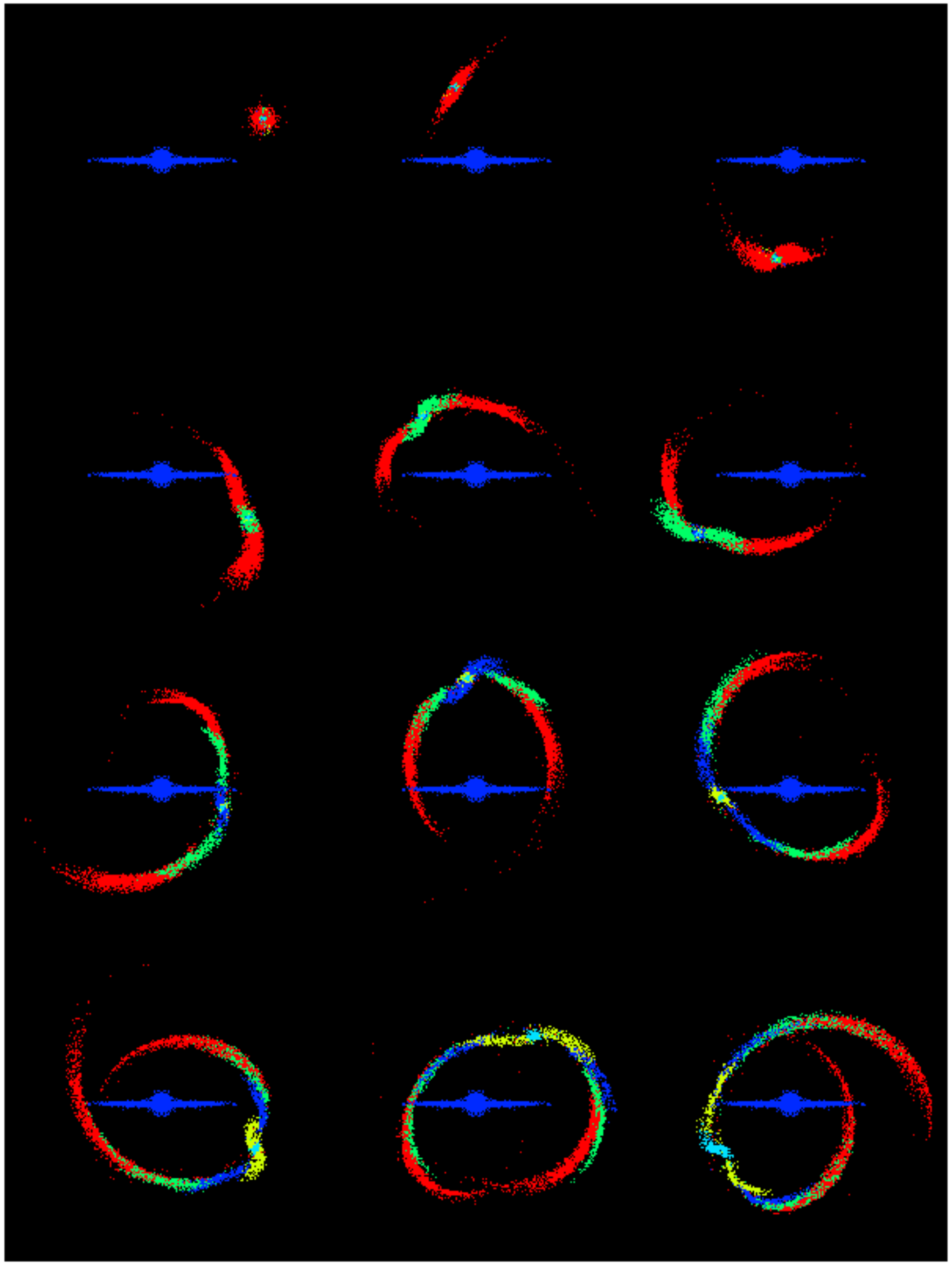


Milky Way Cannibalism



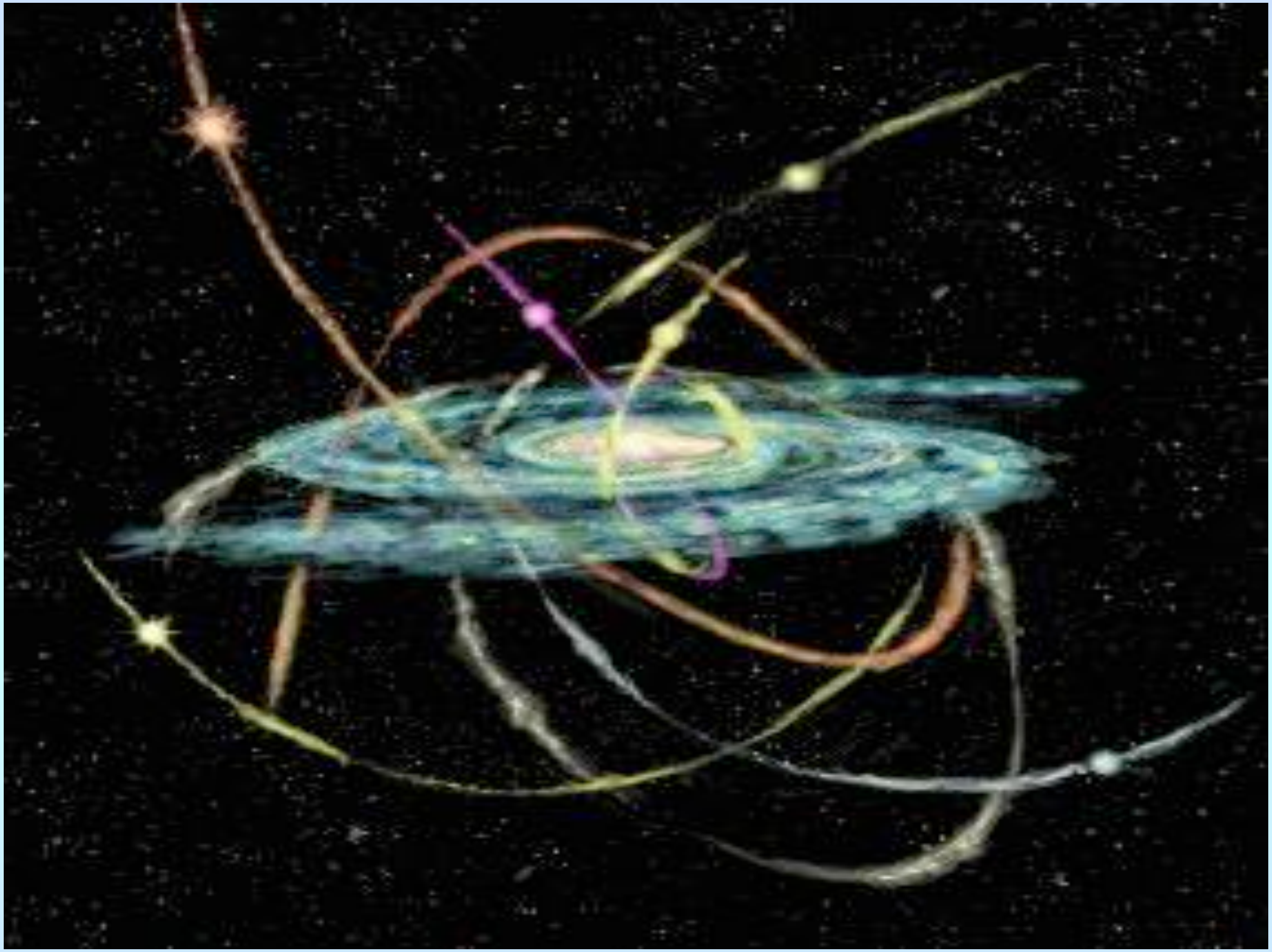
View of the Sagittarius dwarf galaxy

Milky Way Cannibalism



The Sagittarius dwarf galaxy from different viewpoints

Milky Way Cannibalism



One can perform galactic archeology using stellar motions and metallicity measurements